

Effects of Simulated Acidic Rain on Yields of
'Raphanus sativus', 'Lactuca sativa',
'Triticum aestivum' and 'Medicago sativa'

Brookhaven National Lab., Upton, NY

Prepared for

Corvallis Environmental Research Lab., OR

1982

U.S. Department of Commerce
National Technical Information Service

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1. REPORT NO. EPA/600/J-82/466	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Effects of Simulated Acidic Rain on Yields of <i>Raphanus Sativus</i> , <i>Lactuca Sativa</i> , <i>Triticum Aestivum</i> & <i>Medicago Sativa</i> (Journal Version)	5. REPORT DATE 1982	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Lance S. Evans, Nicholas F. Gmur & Dino Mancini	8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Terrestrial & Aquatic Ecology Div., Dept of Energy Brookhaven National Lab, Upton, NY 11973 and Lab of Plant Morphogenesis, Manhattan College, The Bronx, NY 10471	10. PROGRAM ELEMENT NO.	11. CONTRACT/GRANT NO. IAG 81-D-X0533
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Research Laboratory Office of Research and Development U. S. Environmental Protection Agency Corvallis, OR 97333	13. TYPE OF REPORT AND PERIOD COVERED Journal Article	14. SPONSORING AGENCY CODE 600/02
15. SUPPLEMENTARY NOTES Environmental and Experimental Botany 22(4):445-453, 1982 Project Officer: Jeffrey Lee FTS 420-4758		
16. ABSTRACT Experiments were performed to determine effects of simulated acidic rain on radishes (<i>Raphanus sativus</i>), wheat (<i>Triticum aestivum</i>) and alfalfa (<i>Medicago sativa</i>) grown under greenhouse conditions. Experimental designs allowed the detection of statistically significant differences among means that differed by less than 10%. Simulated rainfalls of 2.5, 25, 63, 398, 1000 and 2512 $\mu\text{eq H}^+ \text{l}^{-1}$ (pH 5.6, 4.6, 4.2, 3.4, 3.0 and 2.6, respectively) decreased root yields (fresh mass) of radishes 26, 42, 37, 41, 66 and 73% compared with plants not exposed to rainfalls. Similar reductions were present in radish shoot fresh mass, leaf area, and root diameter. These results suggest that the efficiency of radish foliage in increasing root mass decreases with increased rainfall acidity since only foliage was exposed to the treatments. Yields of lettuce decreased when plants were exposed to acidic simulated rainfalls compared with plants not exposed to rainfalls. Fresh mass yields of lettuce plants exposed to 100, 794, and 1995 $\mu\text{eq H}^+ \text{l}^{-1}$ (pH 4.0, 3.1 and 2.7, respectively) were 11, 10, and 14%, respectively, below heads of plants not exposed to rainfalls. Yields of plants exposed to simulated rainfalls of 2.0 $\mu\text{eq H}^+ \text{l}^{-1}$ (pH 5.7) were similar to plants not exposed to rainfalls.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES
	20. SECURITY CLASS (This page) Unclassified	22. PRICE

EFFECTS OF SIMULATED ACIDIC RAIN ON YIELDS OF *RAPHANUS SATIVUS*, *LACTUCA SATIVA*, *TRITICUM AESTIVUM* AND *MEDICAGO SATIVA*

LANCE S. EVANS,*† NICHOLAS F. GMUR* and DINO MANCINI*‡

*Terrestrial and Aquatic Ecology Division, Department of Energy and Environment,
Brookhaven National Laboratory, Upton, NY 11973, U.S.A

†Laboratory of Plant Morphogenesis, Manhattan College, The Bronx, NY 10471, U.S.A.

(Received 18 December 1981; accepted in revised form 12 April 1982)

EVANS L. S., GMUR N. F. and MANCINI D. *Effects of simulated acidic rain on yields of* *Raphanus sativus*, *Lactuca sativa*, *Triticum aestivum* and *Medicago sativa*. *ENVIRONMENTAL AND EXPERIMENTAL BOTANY* **22**, 445–453, 1982.—Experiments were performed to determine effects of simulated acidic rain on radishes (*Raphanus sativus*), lettuce (*Lactuca sativa*), wheat (*Triticum aestivum*) and alfalfa (*Medicago sativa*) grown under greenhouse conditions. Experimental designs allowed the detection of statistically significant differences among means that differed by less than 10%. Simulated rainfalls of 2.5, 25, 63, 398, 1000 and 2512 $\mu\text{eq H}^+ \text{l}^{-1}$ (pH 5.6, 4.6, 4.2, 3.4, 3.0 and 2.6, respectively) decreased root yields (fresh mass) of radishes 26, 42, 37, 41, 66 and 73% compared with plants not exposed to rainfalls. Similar reductions were present in radish shoot fresh mass, leaf area, and root diameter. These results suggest that the efficiency of radish foliage in increasing root mass decreases with increased rainfall acidity since only foliage was exposed to the treatments. Yields of lettuce decreased when plants were exposed to acidic simulated rainfalls compared with plants not exposed to rainfalls. Fresh mass yields of lettuce plants exposed to 100, 794 and 1995 $\mu\text{eq H}^+ \text{l}^{-1}$ (pH 4.0, 3.1 and 2.7, respectively) were 11, 10 and 14%, respectively, below heads of plants not exposed to rainfalls. Yields of plants exposed to simulated rainfalls of 2.0 $\mu\text{eq H}^+ \text{l}^{-1}$ (pH 5.7) were similar to plants not exposed to rainfalls. Although visible foliar injury occurred to lettuce, this injury was present only on wrapper leaves and would not affect marketable quality. Yields of wheat which were applied during anthesis and caryopsis development were not influenced by exposure to 46 simulated rainfalls even as high as 1995 $\mu\text{eq H}^+ \text{l}^{-1}$ (pH 2.7). Alfalfa plants exhibited no overall differences in fresh mass of forage among treatments even after 57 simulated rainfalls of 1995 $\mu\text{eq H}^+ \text{l}^{-1}$ (pH 2.7) over 105 days.

INTRODUCTION

SIMULATED acidic rain has been shown to produce visible foliar injury of angiosperm and gymnosperm plants if the pH is at or below 3.4 (39 $\mu\text{eq l}^{-1} \text{H}^+$) (5,7,8,13,15,18,20,21,22). Recent evidence^(1,5) suggests that the foliage of herbaceous dicotyledonous plants may be the most sensitive of

all angiosperms and gymnosperms. Experiments were performed to determine growth and yield responses of radish, lettuce, wheat, and alfalfa as a function of hydrogen ion concentration of the simulated rainfall applied. Our overall purpose was to determine (a) which species, and (b) which vital processes of plants are most affected at current and/or anticipated levels of rainfall

‡ Permanent address: Department of Allied Health Sciences, Nassau Community College, Garden City, NY 11530, U.S.A.

acidity.⁽¹⁰⁾ Experiments with radish (*Raphanus sativus*) were performed because LEE *et al.*⁽¹⁶⁾ demonstrated reductions in root mass after exposure to simulated acidic rainfalls. Lettuce (*Lactuca sativa*) was tested because visible foliar injury could decrease market value. Simulated rainfalls were applied to wheat (*Triticum aestivum*) during reproductive stages only to determine if yields might be affected. Alfalfa (*Medicago sativa*) was tested because results of LEE *et al.*⁽¹⁶⁾ suggest that yields of this crop might be stimulated by acidic rain.

MATERIALS AND METHODS

General plant growth techniques

Experiments were performed with radish (*Raphanus sativus*) cv. Cherry Belle, lettuce (*Lactuca sativa* subspecies *capitata*) cv. Ithaca, wheat (*Triticum aestivum*) cv. Waldron, a hard spring wheat, and alfalfa (*Medicago sativa*) cv. Honeoye. In the radish experiment, seeds were planted in 10 cm dia. white plastic pots. Seeds of the other three crops were planted in 15 cm dia. clay pots and allowed to germinate and grow in a greenhouse. The greenhouse was closed to outside air contamination at all times and was equipped with activated charcoal air filters to remove oxidants. The air-conditioned greenhouse temperature did not exceed 30°C. For the radish experiment, Pro Mix BX soil mix (Premier Brands Inc., New Rochelle, NY 10801) was used. For the other three crops a 1:1:1 (v/v) mixture of compost, sand, and peat moss was used. Ground limestone (110 ml) was added to each 100 l of soil for the latter three crops.

In the experiment with radish, a plastic cover was placed on the top of the pots. These covers had a small opening for the seedlings. This procedure minimized soil applications of simulated rain to the root portion of the radish. For the other three crops the soil was not covered. In all experiments, plants were thinned to one plant per pot prior to the first simulated rainfall. During experiments, plants were hand irrigated so that foliage was never exposed to irrigation solution.

Rainfall application procedures

Experimental plants were exposed to simulated rainfalls within an enclosed chamber.⁽⁷⁾ Plants

were placed on a turntable which revolved at 2.5 rev min⁻¹. Simulated acidic rain was distributed from a set of nozzles 1.5 m above the turntable. Each nozzle delivered raindrops of 0.353 mm mean radius.⁽⁷⁾ A vibrator on the nozzle apparatus provided a uniform application of drops. The rain chemistry used in the lettuce, wheat and alfalfa experiments is outlined elsewhere.⁽¹¹⁾ The rain chemistry for the radish experiment is shown in Tables 1 and 2.

Radish experiment

Soil was mounded to a height of 2.5 cm above the rim of the pot. No fertilizers were added. Each simulated rainfall of 7.62 mm was applied during a one-hour time period, three times weekly. A total of 10 rainfalls was applied. The first and last rainfalls occurred when plants were 5 and 30 days old, respectively. Plants were harvested when 32 days old, ten plants per treatment.

Lettuce experiment

Simulated rainfalls of 2.0, 100, 794, and 1995 $\mu\text{eq l}^{-1} \text{H}^+$ (pH 5.7, 4.0, 3.1 and 2.7, respectively) were applied. One treatment consisted of no rainfalls. Simulated rainfalls were applied five times weekly. Each simulated rainfall of 0.34 cm was applied during a 10-min time period. Simulated rainfalls began when plants were 14 days old and ended when plants were 75 days old after 45 rainfalls. Plants were harvested the day after the last rainfall, 26 plants per treatment. A fertilizer solution which contained 141 mg l⁻¹

Table 1. Ionic concentrations* of simulated rainfalls for radish without acidic additions

Ion	Concentration (mg l ⁻¹)
Ca ⁺²	0.165
Mg ⁺²	0.035
K ⁺	0.031
Na ⁺	0.169
NH ₄ ⁺	0.258
Cl ⁻	0.107
PO ₄ ⁻³	0.007

* Weighted mean concentrations for NADP sites for New York, Pennsylvania and Ohio for 1 June–30 September 1979. Values supplied by Dr. Patricia M. Irving.

Table 2. Concentrations of hydrogen, sulfate and nitrate in simulated rainfalls for radish*

	pH 5.6	Ionic concentration (mg l ⁻¹)				
		4.6	4.2	3.4	3.0	2.6
H ⁺	0.0025	0.025	0.063	0.398	1.000	2.512
NO ₃ ⁻	0.457	0.839	1.406	6.444	15.495	38.233
SO ₄ ²⁻	1.114	2.015	3.422	15.239	36.591	90.232

* The sulfate to nitrate mass ratio of 2.37:1.00 was used. This was the sulfate: nitrate mass mean ratio for NADP sites of New York, Pennsylvania, and Ohio for 1 June-30 September 1979. Values calculated by Mr. Keith F. Lewin.

each of nitrogen, phosphorus and potassium was added to the soil of each pot every seven days after plants were 22 days old.

Wheat experiment

Simulated rainfalls of 2.0, 100, 794 and 1995 $\mu\text{eq l}^{-1}$ (pH 5.7, 4.0, 3.1 and 2.7, respectively) were applied. The first rainfall was applied on 42-day-old plants just prior to anthesis. Rainfalls, 10 min in duration (0.34 cm per event total deposition), were applied daily for 46 days until all spikes had mature caryopses. Mature caryopses were harvested in a dry condition. Twenty-four plants per treatment were used. A fertilizer solution which contained 141 mg l⁻¹ each of nitrogen, phosphorus and potassium was added to the soil of each pot 40, 55 and 60 days after planting.

Alfalfa experiment

A slurry (containing 4.5 g inoculant) of Alfalfa and Sweet Clover Inoculant—*Rhizobium meliloti* (North American Plant Breeders Assoc., Princeton, IL 63156) was added to the soil of each pot. A nitrogen-free Hoagland's nutrient solution,⁽¹⁴⁾ which contained 141 mg l⁻¹ each of phosphorus and potassium, was added to alfalfa pots every seven days starting when plants were 47 days old. The first rainfall was applied when plants were 20 days old (plants were 5 cm in height). Rainfalls, 10 min in duration (0.34 cm total deposition per event), were applied five times per week to provide a total of 57 rains. Plants were harvested on days 60, 85 and 106. Plants were cut 5 cm above the soil level. Twenty-five plants per treatment were used.

Statistical analysis

Statistical analyses were performed on all data to determine if treatment means were significantly different at the $p < 0.05$ confidence level. Analysis of variance, followed by the Student-Newman-Keuls multiple range test was performed in order to determine significance.⁽¹⁹⁾

RESULTS

Radish

One set of plants was not exposed to rainfalls. Plants exposed to simulated rainfalls of pH 5.6, 4.6, 4.2, 3.4, 3.0 and 2.6 provided H⁺ concentrations of 2.5, 25, 63, 398, 1000 and 2512 $\mu\text{eq l}^{-1}$, respectively. These same rainfall treatments provided total depositions of 1.54, 15.4, 38.9, 246, 618 and 1550 $\mu\text{eq H}^+$ after 10 exposures. Fresh masses of both roots and shoots were markedly smaller in plants exposed to acidic rainfalls compared with plants exposed to more neutral rainfalls. Simulated rainfalls of 2.5, 25, 63, 398, 1000 and 2512 $\mu\text{eq l}^{-1}$ H⁺ concentration decreased root (fresh mass) yields 26, 42, 37, 41, 66 and 73%, respectively, compared with plants not exposed to rainfalls (Fig. 1; Table 3). Similar reductions were present in shoot fresh mass (Fig. 1). Dry masses of roots and shoots were between 4.9 to 5.4% and 7.5 to 8.2%, respectively, of fresh masses.

Decreases in shoot fresh mass at higher simulated rainfall acidities were reflected in decreases in leaf area (Fig. 2; Table 3). In a similar manner, decreases in diameter of harvested roots were similar to reductions in both fresh and dry masses of roots (Fig. 2; Table 3). Plants exposed to

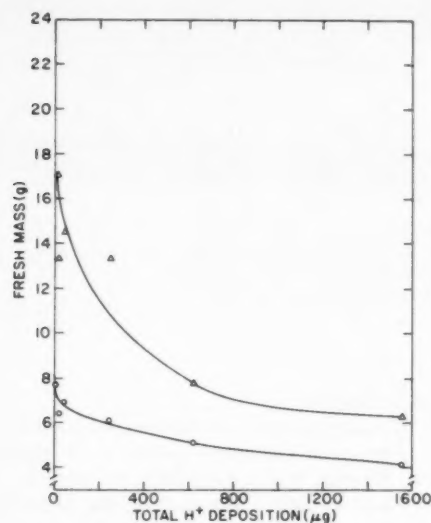


FIG. 1. Rainfall acidity response relationships of fresh mass of roots (triangles) and shoots (circles) of radish exposed to simulated rainfalls with various hydrogen ion concentrations. Smooth lines were drawn to pass as close to as many data points as possible. Values for plants not exposed to simulated rainfalls are not included.

simulated rainfalls of 2.5, 25, 63, 398, 1000 and 2512 $\mu\text{eq l}^{-1} \text{H}^+$ concentration had shoot/root fresh mass ratios of 0.46, 0.49, 0.52, 0.47, 0.72 and

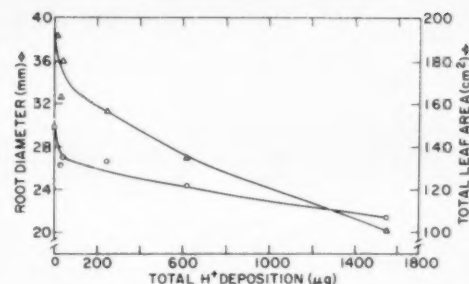


FIG. 2. Rainfall acidity response relationships of root diameter (circles) and total leaf area (triangles) of radish exposed to simulated rainfalls with various hydrogen ion concentrations. Smooth lines were drawn to pass as close to as many data points as possible. Values for plants not exposed to simulated rainfalls are not included.

0.72, respectively, compared with a 0.34 ratio of plants not exposed to rainfalls. Simulated rainfalls of high acidity increased the shoot-to-root ratio (Table 4). In general, plants exposed to simulated rainfalls of 1000 and 2512 $\mu\text{eq l}^{-1} \text{H}^+$ concentration had ratios twice as high as plants exposed to lower acidity rainfalls. A similar increase in fresh root mass per unit of leaf area also occurred (Table 4). These results suggest that foliage of radishes exposed to simulated rainfalls greater than 25 $\mu\text{eq l}^{-1} \text{H}^+$ have lower efficiencies in terms of root biomass production compared with

Table 3. Effects of simulated acidic rainfalls on growth and yield parameters of radish*

Treatment H ⁺ concentration of rainfalls: ($\mu\text{eq l}^{-1}$)	Fresh mass shoot (g plant ⁻¹)	Fresh mass root (g plant ⁻¹)	Dry mass shoot (g plant ⁻¹)	Dry mass root (g plant ⁻¹)	Leaf surface area (cm ² plant ⁻¹)	Root diameter (mm)
(a) Plants unexposed to rainfalls	7.61 ^a	23.0 ^a	0.58 ^a	1.12 ^a	188 ^{a,b}	34.0 ^a
(b) 2.5 (pH 5.6)	7.74 ^a	17.1 ^b	0.59 ^a	0.86 ^b	193 ^a	29.7 ^b
(c) 25 (pH 4.6)	6.39 ^{a,b}	13.3 ^c	0.48 ^{a,b}	0.69 ^{c,d}	163 ^{a,b,c}	26.3 ^{b,c}
(d) 63 (pH 4.2)	6.89 ^{a,c}	14.6 ^{b,c}	0.54 ^a	0.77 ^{b,d}	180 ^{a,b}	27.3 ^{b,d}
(e) 398 (pH 3.4)	6.10 ^{b,c,d}	13.4 ^c	0.48 ^a	0.70 ^{c,d}	154 ^{b,e}	26.7 ^{b,e}
(f) 1000 (pH 3.0)	5.16 ^{b,d,e}	7.74 ^d	0.39 ^{b,c}	0.41 ^e	135 ^{c,d,e}	24.4 ^{c,d,e,f}
(g) 2512 (pH 2.6)	4.16 ^e	6.25 ^d	0.34 ^c	0.34 ^e	102 ^f	21.6 ^f

* For each parameter measured, values not followed by the same letter are significantly different ($p \leq 0.05$) according to the Student-Newman-Keuls multiple range test.⁽¹⁹⁾ Values followed by the same letter are not significantly different.

Table 4. Effects of simulated acidic rainfalls on ratios of various growth and yield parameters of radish*

Treatment H ⁺ concentration of rainfalls ($\mu\text{eq l}^{-1}$)	Ratio (per plant basis)			
	Fresh mass (shoot / root)	Dry mass (shoot / root)	Shoot mass (fresh / dry)	Leaf area (cm^2) Fresh mass root (g)
(a) Plants unexposed to rainfalls	0.34 ^a	0.52 ^a	13.1 ^{a,b}	8.34 ^a
(b) 2.5 (pH 5.6)	0.46 ^a	0.67 ^a	13.3 ^a	11.3 ^a
(c) 25 (pH 4.6)	0.49 ^a	0.70 ^a	13.3 ^a	12.5 ^a
(d) 63 (pH 4.2)	0.52 ^{a,c}	0.75 ^a	12.7 ^{a,b}	13.4 ^a
(e) 398 (pH 3.4)	0.47 ^a	0.69 ^a	12.7 ^{a,b}	11.8 ^a
(f) 1000 (pH 3.0)	0.72 ^{b,c}	1.01 ^b	13.5 ^a	18.8 ^b
(g) 2512 (pH 2.6)	0.72 ^b	1.08 ^b	12.3 ^b	17.6 ^b

* For each parameter measured, values not followed by the same letter are significantly different ($p \leq 0.05$) according to the Student-Newman-Keuls multiple range test.⁽¹⁹⁾ Values followed by the same letter are not significantly different.

plants exposed to acidities less than $25 \mu\text{eq l}^{-1} \text{H}^+$ since only shoots received simulated rainfall applications. The ratio of fresh mass of leaves per unit leaf area remained constant (mean = 0.04 g cm^{-2}) among all treatments.

No foliar injury occurred on plants unexposed to simulated rainfalls. Visible foliar injury occurred on foliage of plants exposed to 398, 1000 and $2512 \mu\text{eq H}^+ \text{l}^{-1}$ within 20 hr after the first simulated rainfall. After the first simulated rainfall, injury was most predominant on cotyledons. First true leaves showed injury only at 1000 and $2512 \mu\text{eq H}^+ \text{l}^{-1}$ rainfalls. After several rainfalls some leaf injury appeared on cotyledons and first true leaves of plants exposed to $63 \mu\text{eq l}^{-1} \text{H}^+$. The amount of foliar injury to these latter plants remained low throughout the experiment. No foliar injury was detected on foliage of plants exposed to simulated rainfalls of 2.5 and $25 \mu\text{eq l}^{-1} \text{H}^+$. These results are similar to those found in other species such as pinto beans, sunflower and spiderwort.^(5,7)

Lettuce

Fresh mass yields of lettuce decreased when plants were exposed to simulated rainfalls of 100, 794 and $1955 \mu\text{eq H}^+ \text{l}^{-1}$ compared with plants

unexposed to rainfalls (Table 5). Simulated rainfalls of 2, 100, 794 and $1995 \mu\text{eq l}^{-1}$ had lettuce head fresh masses that were 5, 11, 10 and 14%, respectively, lower than heads of plants unexposed to simulated rainfalls. Fresh mass yields of plants exposed to $2 \mu\text{eq l}^{-1}$ rainfalls were not significantly different from unexposed controls (Table 5). Dry mass of heads was significantly affected by simulated rainfalls only at the highest acidity level ($1995 \mu\text{eq l}^{-1}$) used. Even though visible foliar injury was present in plants exposed to rainfalls of 794 and $1995 \mu\text{eq l}^{-1}$, these injuries occurred on wrapper leaves that would normally be removed during processing for market.

Wheat

Yields of wheat were not influenced by exposure to simulated rainfalls as high as $1995 \mu\text{eq l}^{-1}$ when plants were exposed throughout anthesis and caryopsis development. No statistically significant differences were present among values for any parameter measured (Table 6). Other experimental parameters such as number of tiller spikes, number of tiller spike caryopses, and mean mass of tiller spike caryopses per plant were measured (data not shown) resulting in a similar

Table 5. *Effects of acidity of rainfalls on yield parameters of lettuce**

Parameter (per plant)	Treatment				
	No rainfalls	Simulated rainfall ($\mu\text{eq l}^{-1}$)			
		2.0 (pH 5.7)	100 (pH 4.0)	794 (pH 3.1)	1995 (pH 2.7)
Fresh mass of heads (g)	373.8 ^a	354.5 ^{a,b}	334.5 ^{b,c}	338.1 ^{b,c}	320.7 ^c
Dry mass of heads (g)	14.8 ^a	15.2 ^a	14.9 ^a	14.9 ^a	12.8 ^b
Dry mass of excess leaves (g)	1.3 ^a	1.4 ^a	1.3 ^a	1.1 ^{a,b}	0.8 ^b
Dry mass of roots (g)	3.6 ^{a,b}	3.3 ^{a,b}	3.7 ^a	3.2 ^{a,b}	2.5 ^b
Total dry mass (g)	19.6 ^a	19.9 ^a	19.9 ^a	19.2 ^a	16.1 ^b

* For each parameter measured, numbers not followed by the same letter are significantly different ($p \leq 0.05$) according to the Student-Newman-Keuls multiple range test.⁽¹⁹⁾ Values followed by the same letter are not significantly different.

lack of statistical differences. Little visible foliar injury occurred.

Alfalfa

Alfalfa plants were exposed to a total of 57 simulated rainfalls. Except for a small but statistically significant increase in first harvest shoot fresh mass yield of plants exposed to rainfalls of 794 $\mu\text{eq l}^{-1}$ compared with other treatments, no significant changes in yield due to increased rain

acidity occurred among treatments (Table 7). With all harvests combined, the fresh mass of all treatments varied from 49.3 to 60.3 g per plant. No statistically significant differences were present for other experimental parameters such as height of tallest shoot, number of inflorescences, dry mass of stems, and dry mass of leaves (data not shown).

Visible injury was present on foliage of some plants exposed to simulated rainfalls of 100, 794

Table 6. *Effects of acidity of rainfalls on yield parameters of wheat**

Parameter (per plant)	Treatment				
	No rainfalls	Simulated rainfall ($\mu\text{eq l}^{-1}$)			
		2.0 (pH 5.7)	100 (pH 4.0)	794 (pH 3.1)	1995 (pH 2.7)
Mean number of mature spikes	6	6	6	6	5
Mean number of caryopses on mature spikes	139	120	152	122	119
Mean dry mass of caryopses	5.9	5.1	6.1	5.1	5.0
Mean number of all caryopses	171	132	171	136	141
Mean mass of all caryopses	6.8	5.5	6.7	5.6	5.8

* No statistically significant differences among mean values for any parameter were detected.

Table 7. Effects of acidity of rainfalls on yield parameters of alfalfa*

Parameter (per plant)	Treatment				
	No rainfalls	Simulated rainfall ($\mu\text{eq l}^{-1}$)			
		2.0 (pH 5.7)	100 (pH 4.0)	794 (pH 3.1)	1995 (pH 2.7)
<i>Harvest no. 1</i>					
Mean fresh mass of shoots (g)	18.9 ^c	15.3 ^b	16.5 ^{b,c}	21.6 ^a	17.7 ^{b,c}
Mean dry mass of shoots (g)	3.3 ^{c,d}	2.7 ^c	2.9 ^{b,c}	3.7 ^{a,d}	3.2 ^{c,d}
<i>Harvest no. 2</i>					
Mean fresh mass of shoots (g)†	20.1	16.9	18.2	19.6	18.5
Mean dry mass of shoots (g)†	3.6	2.9	3.2	3.4	3.3
<i>Harvest no. 3</i>					
Mean fresh mass of shoot (g)†	20.2	17.1	16.9	19.1	16.5
Mean dry mass of shoots (g)†	3.7	2.9	3.2	3.4	3.0
<i>All harvests combined</i>					
Mean total fresh mass of shoots (g)†	59.2	49.3	51.6	60.3	52.7
Mean total dry mass of shoots (g)	10.5 ^a	8.6 ^{b,c}	9.3 ^{a,c}	10.5 ^a	9.5 ^{a,c}

* For each parameter measured, values not followed by the same letter are significantly different ($p \leq 0.05$) according to the Student-Newman-Keuls multiple range test.⁽¹⁹⁾ Values followed by the same letter are not significantly different.

† No statistically significant differences among mean values for any parameter were detected.

and 1995 $\mu\text{eq H}^+ \text{l}^{-1}$. No foliar injury was present on plants exposed to simulated rainfalls of 2 $\mu\text{eq l}^{-1}$ or plants not exposed to simulated rainfalls. Young, expanding leaves were more affected than were completely expanded leaves. Foliar injury, when present, was similar to that found on soybean leaves.⁽⁵⁾ At any one time, only about 2% of the foliage of plants exposed to simulated rainfalls of 794 and 1995 $\mu\text{eq H}^+ \text{l}^{-1}$ exhibited visible injury.

DISCUSSION

These experimental results coupled with results of other experiments document that acidic rain has diverse effects on plant growth and productivity.⁽²⁾ It is clear that plants must be tested on a

species-by-species, or even a cultivar-by-cultivar, basis.

Plants exposed to simulated rainfalls of 2 $\mu\text{eq l}^{-1}$ had values similar to plants that did not receive any simulated rainfalls. In almost all cases mean values of unexposed plants were above all mean values of plants that received simulated rainfalls. This relationship also holds for field-grown plants which when exposed to ambient rainfalls have better growth than plants exposed to simulated rainfalls in addition to ambient rainfalls.⁽⁴⁾ In this way, rainfalls by themselves may affect plant growth and productivity. It is obvious that nutrient balances and gas exchange characteristics may differ significantly among unexposed plants and plants exposed to rainfalls.⁽⁶⁾

LEE *et al.*⁽¹⁶⁾ showed root crops may be preferentially affected by acidic precipitation. In their experiments, root yields of radish, garden beet and carrot were significantly decreased by simulated acidic precipitation. This paper presents similar results. Both experiments were conducted with potted plants. Results of these two experiments are significantly different from those of field-grown radish.⁽⁴⁾ Although several differences in experimental design existed between potted plant and field-grown radish, potted plants exposed to simulated acidic rainfalls exhibited foliar injury concomitant with root mass reductions. In field-grown radish, neither foliar injury nor reductions in root mass were observed.⁽⁴⁾

Although visible foliar injury may be correlated with decreases in crop productivity, visible foliar injury was not responsible for the significant reduction in lettuce yield. Visible foliar injury occurred only on outer wrapper leaves of lettuce; these leaves would normally be removed before plants are marketed. Even though lettuce leaves are succulent (96% of total mass is water), their foliage is less sensitive than leaves of pinto bean or soybeans grown under greenhouse conditions.^(5,10)

Foliar injury to wheat was very sparse and only occurred on foliage exposed to simulated rainfalls of 794 and 1995 $\mu\text{eq H}^+ \text{ l}^{-1}$. Most lesions were less than 0.5 mm in diameter. This response is similar to that of *Tradescantia*.⁽⁵⁾ This experimental design was used to test if simulated acidic rainfalls could decrease productivity through loss of photosynthate from the flag leaf and glumes to the caryopses since these plant portions provide the majority of caryopsis photosynthate. Because yield was not altered it may be predicted that wheat is quite insensitive to acidic precipitation.

Alfalfa also appears to be insensitive. No statistically significant change in fresh mass of shoots was detected even though plants were exposed to 57 simulated rainfalls over a period of 105 days. Similar results were present when alfalfa plants were exposed to simulated acidic rainfalls under agronomic conditions.⁽¹²⁾ We suggest that the very high contact angle of water droplets on leaves of alfalfa (personal observation) and wheat would minimize the wettability of foliage of these two crops.^(2,17)

Experimental exposures of plants to simulated acidic precipitation over days, weeks, or a growing season are conducted to evaluate relationships between treatment H^+ concentrations and plant responses. In evaluating experimental results, it is important to distinguish between effects observed at H^+ concentrations which are much above the volume-weighted mean H^+ concentration of ambient precipitation, near ambient H^+ levels, and so-called 'control' H^+ levels (e.g. pH 5.6) which are much below ambient levels. Both extremes do not occur frequently in the north-eastern United States. However, when a large range of H^+ concentrations is tested, linear or curvilinear functions with known confidence limits of plant responses versus H^+ concentrations will provide information to estimate changes in plant response due to present or anticipated levels of ambient rainfall acidity.

Since results of potted plants differ from plants exposed to simulated acidic rain under agronomic conditions,^(3,4,10) results with potted plants must be evaluated with caution. From available evidence, plants exposed to acidic precipitation under greenhouse conditions are more sensitive to acidic precipitation than plants grown under field conditions. As a result it seems reasonable to suggest that a survey of only relative sensitivity can be conducted under greenhouse conditions before field experiments. It seems reasonable to conclude that plants insensitive to simulated acidic rainfalls of pH 3.5 under greenhouse conditions will not be adversely affected by ambient rainfalls at or above pH 3.5 out-of-doors. If this is true, only plant species sensitive to acidic precipitation under greenhouse conditions need be tested under ambient conditions.

The impacts, if any, that acidic precipitation is having on terrestrial plants outside of laboratory or controlled field conditions have yet to be determined accurately.⁽⁹⁾ Experimental research to date has shown that plant response can vary greatly depending on species, environment, and method of exposure. Due to this variability, it has been necessary to study impacts of acidic precipitation on a plant species by plant species (and maybe a cultivar by cultivar) basis. From this approach an overall picture of which plant groups are most sensitive and the types of injury which occur is beginning to emerge.^(1,5)

Acknowledgements—This research was supported by the United States Environmental Protection Agency, Office of Research and Development, under IAG 81-D-X0533, and by United States Department of Energy, under Contract No. DE-AC02-76CH00016 and in part by Associated Universities, Inc., under Contract No. 550925-S. The experiment with radish was conducted when several other laboratories in North America were conducting similar experiments.

REFERENCES

1. EVANS L. S. (1980) Foliar responses that may determine plant injury by simulated acid rain. Pages 239–257 in T. TORIBARA, M. MILLER and P. MORROW, eds, *Polluted rain*, 12th Ann. Rochester Int. Conf. on Environmental Toxicity, Plenum Press, New York.
2. EVANS L. S. (1982) Biological effects of acidity in precipitation on vegetation: a review. *Environ. Exp. Bot.* **22**, 155–169.
3. EVANS L. S., CONWAY C. A. and LEWIN K. F. (1980) Yield responses of field-grown soybeans exposed to simulated acid rain. Pages 162–163 in D. DRABLO and A. TOLLAN, eds, *Ecological impact of acid precipitation*, SNSF Project, Ås-NLH, Norway.
4. EVANS L. S., CUNNINGHAM E. A. and LEWIN K. F. (1981) Effects of simulated acidic rain on field-grown radishes and garden beets. Pages 82–85 in *Proc. 182nd Mtg of the Am. Chem. Soc.*
5. EVANS L. S. and CURRY T. M. (1979) Differential responses of plant foliage to simulated acid rain. *Am. J. Bot.* **66**, 953–962.
6. EVANS L. S., CURRY T. M. and LEWIN K. F. (1981) Responses of leaves of *Phaseolus vulgaris* to simulated acidic rain. *New Phytol.* **88**, 403–420.
7. EVANS L. S., GMUR N. F. and DA COSTA F. (1977) Leaf surface and histological perturbations of leaves of *Phaseolus vulgaris* and *Helianthus annuus* after exposure to simulated acid rain. *Am. J. Bot.* **64**, 903–913.
8. EVANS L. S., GMUR N. F. and DA COSTA F. (1978) Foliar responses of six clones of hybrid poplar to simulated acid rain. *Phytopathology* **68**, 847–856.
9. EVANS L. S., HENDREY G. R., STENSLAND G. J., JOHNSON D. W. and FRANCIS A. J. (1981) Acidic precipitation: consideration of an air quality standard. *Water, Air, Soil Pollut.* **16**, 469–509.
10. EVANS L. S. and LEWIN K. F. (1981) Growth, development and yield responses of pinto beans and soybeans to hydrogen ion concentrations of simulated acidic rain. *Environ. Exp. Bot.* **21**, 103–113.
11. EVANS L. S., LEWIN K. F., CONWAY C. A. and PATTI M. J. (1981) Seed yield (quantity and quality) of field-grown soybeans exposed to simulated acidic rain. *New Phytol.* **89**, 459–470.
12. EVANS L. S., LEWIN K. F., CUNNINGHAM E. A. and PATTI M. J. (in press) Effects of simulated rain on yields of field-grown crops. *New Phytol.*
13. FERENBAUGH R. W. (1976) Effects of simulated acid rain on *Phaseolus vulgaris* L. (Fabaceae). *Am. J. Bot.* **63**, 283–288.
14. HOAGLAND D. R. and ARNON D. J. (1950) The water culture method of growing plants without soil. *Calif. Agric. Exp. Stn. Circ.* **347**, 1–32.
15. JOHNSON B. and SUNDBERG R. (1972) Has the acidification by atmospheric pollution caused a growth reduction in Swedish forests? A comparison of growth between regions with different soil properties, in B. BOLIN, ed. *Supporting studies to air pollution across national boundaries. The impact on the environment of sulfur in air and precipitation*. Sweden's Case Study for the United Nations Conference on The Human Environment. Royal Ministry of Foreign Affairs, Royal Ministry of Agriculture, Stockholm, 46 pp.
16. LEE J. J., NEELY G. E., PERRIGAN S. C. and GROTHAUS L. C. (1981) Effect of simulated sulfuric acid rain on yield, growth and foliar injury of several crops. *Environ. Exp. Bot.* **21**, 171–185.
17. MARTIN J. T. and JUNIPER B. E. (1970) *The cuticles of plants*. St. Martin's Press, New York.
18. SHRINER D. S. (1977) Effects of simulated rain acidified with sulfuric acid on host-parasite interactions. *Water, Air, Soil Pollut.* **8**, 9–14.
19. STEEL R. G. and TORRIE J. H. (1960). Page 481 in *Principles and procedures of statistics*. McGraw-Hill, New York.
20. WOOD T. and BORMANN F. H. (1974) The effects of an artificial mist upon the growth of *Betula alleghaniensis*. (Britt.) *Environ. Pollut.* **7**, 259–268.
21. WOOD T. and BORMANN F. H. (1975) Increases in foliar leaching caused by acidification of an artificial mist. *Ambio* **4**, 169–171.
22. WOOD T. and BORMANN F. H. (1977) Short-term effects of a simulated acid rain upon the growth and nutrient relations of *Pinus strobus*, L. *Water, Air, Soil Pollut.* **7**, 479–488.

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